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State-of-the-art Laser Additive Manufacturing for Hot-work Tool Steels

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Abstract

Additive manufacturing (AM) processes are based on the controlled selective deposition of material by which a part is manufactured or remanufactured (repaired), layer by layer. Research in AM is drastically on the increase in the last several years owing to the benefits that AM provides over conventional manufacturing i.e. reduction in material usage, time-to-market reduction, improved functionality, increased ability to customize and near-net shape manufacturing. There has been a number of AM techniques focused on non-metallic materials. In addition, many industries have already embraced the use of AM for metallic parts using laser as an efficient machining tool, including automotive, die & mold, aerospace & defense, industrial products, consumer products and health care. However, the research on metallic materials has been facing a lot of obstacles due to the complexity involved in laser additive manufacturing (LAM) process. This complexity arrives from a multitude variables involved in the process itself i.e. system design as well as process design variables. As a result, there are nowadays limited AM technologies commercially available. This can motivate researchers to focus their work in order to ruggedize LAM processes for commercial large-scale. In this regard, this paper gives the definition and classification of additive manufacturing processes according to ASTM Standard F2792-12a, followed by a description of principles and future perspectives for fabrication of parts via LAM focused on hot-work tool steels, and potential future applications of LAM for industries i.e. die & mold, forging and cutting tools and automotive. The present paper also talks about the barriers to implementation of LAM for hot-work tool steels.

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1. Introduction

Additive manufacturing is a process for making free-formed parts by adding material layer-by-layer in an efficient way. AM uses a tool path, which divides the desired parts into 2D layers as compared to conventional process. Subsequently, these layers are deposited to build up the complete part. This procedure has a number of advantages over conventional process. For instance, the potential to perform rapid prototyping and fabrication of complex products with blind machining features like cooling channels. AM has particularly achieved a lot of success in producing 3D parts made of polymers because of their low melting point and high viscosity, which allow a simple heat input system and nozzle designs to be used for precise deposition [1]. However, the potential of AM in building functional parts has still to be studied for a wider range of metal alloys especially hot-work tool steels.

Laser additive manufacturing (LAM) is one of the most important AM processes for processing metal alloys. To date, several LAM processes have been developed and commercialized to build and/or repair functional metal parts. For instance, laser metal deposition (LMD), selective laser sintering (SLS) and selective laser melting (SLM). LAM is also considered as a cost-effective and near-net shape rapid manufacturing process, if hard-to-machine materials have to be manufactured [2]. It is used to directly manufacture fully dense and complex 3D parts like biomedical components or aero engine components [3, 4, 5]. LMD is implemented to build molding die inserts and light reflectors. The goal of all these LAM processes has been to minimize raw material usage, lead time for part production and manufacturing costs

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while improving the performance and quality of the end product [6].

The motivation for LAM is also driven by advanced materials and energy considerations and by industry demands. The design of highly critical mechanical products often rely on advanced materials to achieve required performance characteristics [7]. One material group, which guarantees a success for several industries, is the group of hot-working steels. They are widely used in different industries to produce highly stressed hot-work tool steel products such as molds and dies for extrusion, forging and die casting tools. Conventional processes such as casting, vacuum arc remelting (VAR) and powder metallurgy (PM) are generally used to produce these steels. However, these processes possess critical drawbacks. For example, in the case of casting, the process leads to a coarse microstructure, which is not desirable to achieve the best material properties, and although PM greatly controls the microstructure-property relation, it contains a number of critical steps, which make the process expensive [8].

From a manufacturing standpoint, therefore the challenges for LAM technologies required to transfer materials into final products have drastically raised. Each material possesses specific characteristics that make them applicable candidate for a particular application. In this respect, hot-work tool steels possess strength-at-high-temperature, which makes them an appropriate choice for hot-working applications. Nevertheless, LAM is seldom used to manufacture mechanical parts made up of these steels. Hence, the present paper addresses the challenges that make LAM less applicable to manufacture such kind of products. Furthermore, this paper is outlined to articulate the-state-of-the-art LAM in terms of manufacturing products of hot-work tool steels. It also talks about some important LAM processes and their application in order to fabricate such products.

2. Classification of laser additive manufacturing

Based on ASTM F2792-12A Standard Terminology for Additive Manufacturing Technologies, the following definition has been introduced: Additive Manufacturing (AM) is the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies [6]. The wording 'the process of joining materials' means that AM has an ability to join the same materials or different materials together. This ability is used in LAM process to fabricate metallic parts. LAM has emerged with the introduction of SLS in 1987. As partially molten powder has been a problem in the beginning of metal powder-bed fusion, which is not a desired process feature, SLS is used purely for plastic processing today. Since then, a number of LAM processes have been developed to build and/or repair parts made of hot-work tool steels.

According to the ASTM F42 Committee, AM processes based on laser and pertained to metal are SLM and wire- and powder-fed direct energy deposition (DED): Direct metal deposition process (DMD) belongs to DED [9]. Fig. 1 gives a classification of LAM processes implemented for hot-work tool steels. Their application focuses on the production or repair of functional parts; for example, gear mold insert, landing gears, and gas turbine blade. Therefore, these processes have been used in various industries; for instance, space, aircraft, biomedical, automotive and architecture [10].

Process type	Brief description	Related technologies	Applications
Powder bed fusion	Laser energy selectively fuses regions of a powder bed	Selective laser melting (SLM)	Prototypes, short run dies, tooling, functional parts
Direct energy deposition	Laser energy is used to melt and join materials	Powder- and wire-based laser metal deposition (LMD)	Complex and larger dies, tooling, part repair, functional parts
Hybrid process	It combines LAM with CNC machining	Hybrid metal manufacturing	Functionally graded materials (FGMs), part repair, inserts with conformal cooling

Fig. 1. Classification of laser additive manufacturing (LAM) [6, 35, 39].

3. Laser additive manufacturing of metallic materials

LAM plays a crucial role to reduce the production costs especially when machining high-cost, hard-to-cut or hard-to-bend metallic materials. It has a number of working principles considering its application. For surface integrity applications, the substrate can be a wrought product, a forging, a casting or a damaged part. LAM can be achieved by hybrid fusion-based processes, which use additional energy source such as an electron beam, a plasma beam, and/or an electric arc and metallic powder and/or wire as feedstock [4, 6, 10].

Although LAM offers a number of benefits in terms of production lead-time, acquisition cost and performance envisioned, there are significant challenges while developing LAM for metallic material. These challenges are obvious in light of a number of physical phenomena involved in the process and unavailability of their knowledge. Hence, most of LAM processes have been used to enhance the surface integrity of metallic parts i.e. to improve wear, corrosion and oxidation resistance, and to some extent fatigue resistance [11, 12]. Additionally, LAM can be used to produce functionally graded materials (FGMs) [13] because it has capability to handle various materials at the same time [14]. LAM is particularly attractive for the production of aerospace parts because it can greatly increase fly-to-buy rations [15, 43]. However, applications of the LAM process are limited mostly to repair a part, and it has been seldom used to build up complete parts from hot-work tool steels. The reasons for this are the difficulties involved while introducing heat into this material, availability of cost-effective conventional processes, and the industries wherein hot-work tool steel fits are not as critical as aerospace industry.

3.1. Process characteristics of LAM for metallic materials

LAM for metallic materials are fusion-based processes built upon traditional welding technologies. Variations in energy input, filler material deposition rates and laser scan speeds produce a wide variety of alloys, microstructures and geometries due to an undercooling effect [15-17]. Therefore, LAM can be implemented to manufacture and investigate experimental alloys because of its better control over the